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13. ABSTRACT *(Maximum 200 words)*

A brief description is given for sixteen fellows that studied at the ERC with the support of this grant. The individual research summaries are followed by a listing of the Ph.D. theses and publications for each fellow.

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F I N A L   R E P O R T

DAAL03-86-G-0200

Dr. G.L. Borman

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INTRODUCTION

The Army Fellows program summarized in this report was an integral part of the funding package which was setup to create the U.S. Army Center of Excellence in Advanced Propulsion starting in fiscal year 1986 and supported for a period of five years. The fellowships allowed the Center to attract outstanding U.S. citizen doctoral students and thus assured the ability of the Center to train students for future work in U.S. industries, government, and universities.

Each fellow was supported by the grant for a period of three years. Each fellow had received an M.S. degree prior to starting the fellowship. In a majority of cases, the fellows had work experience between the M.S. degree and the start of the Ph.D. program. Attracting such people back from industry for advanced study would have been very difficult without the fellowship program.

The three year program was not long enough to allow completion of the degree for the fellows and thus some of the fellows received an additional year of support from research funds or from industrial fellowships supplied by General Motors and Chevron Research. The GMC Fellowships supported four of the fellows (D. Boggs, J. Hodges, J. Naber, and D. Richardson) for one year each.

In many cases, the research of the fellow was closely connected to industrial co-operative efforts. Examples of co-operation include: John Deere and G. Green, GMRL and J. Naber, Amoco and D. Tree, Exxon and J. Myers, Cummins and D. Richardson, Detroit Diesel and J. Shakal.

It should be noted, for future programs of this sort, that the fellowship stipend level had to be increased significantly early in the program, because of a change in the tax law which required significant increases in stipends paid to research assistants. The fellows program remained competitive during the five years mainly due to the fact that only second and third year fellows remained during the last two years. The first year fellows stipend level would have been noncompetitive if applied during the last two years.

Competition for the very best U.S. citizen doctoral candidates has become very intense in the last few years. Without fellowship programs, it is difficult to win the competition. The use of fellowship programs connected to specific research contracts is thus important as it greatly improves the chances that the best people will be trained in the areas preselected by the funding agency as the most important.

The program produced sixteen Ph.D.'s, all that could be accommodated by the allowed funding level. Each of these doctorates have been trained in specific research of vital concern to the U.S. Army and of equal importance to U.S. industry. They particularly benefitted from the excellent facilities of the Center made possible by the parallel equipment grant and thus have experience with modern advanced instrumentation and computational methods.

In the paragraphs below, a summary of the highlights of the research for all the fellows is given to help the reader understand the impact of the research. The research projects conducted by the fellows covered a broad spectrum of the ERC research program topics. The programs may be divided into four broad categories of topics: sprays; fluids and heat transfer; combustion, fuels, and emissions; and materials, mechanical design, and lubrication.

The subject of spray behavior in diesels is a major area of study in the ERC, covering both injector and spray characteristics. The program has attempted to include the most current issues such as high pressure injection and injection rate shaping.

As injector design has become more sophisticated, it has become more important to understand the details of the flow in the injector itself, particularly the injector nozzle. It is known from empirical observation that the injector tip hole length to diameter ratio is an important parameter in determining the spray breakup, yet no current spray model includes this effect. Because the hole diameter is very small (0.2 mm) and the length very short (1-2 mm), it is difficult to study the details of flow behavior in the hole. Thus Army Fellow Andrea Knox-Kelecy has used a scaled-up model of the injector tip to study these details. The results, showing significant axial rms velocity and turbulent spectra differences, remain to be connected to observed differences in the spray breakup behavior as obtained by other researchers in the ERC. The results are also important for understanding small differences in injector tips which lead to variations in engine-out emissions.

In addition to better tip design, modern diesel injectors also offer the potential for rate shaping. While it is known that the rate shape is important, the ability to drastically and predictively change the shape is a recent event which is only available as yet in prototypes. Two types of shape changes are important, the use of a pilot injection (split injection) and the change shape of the main injection with or without a preceding pilot injection.

Army Fellow Joe Shakal is investigating pilot injection in a two-stroke diesel. His early studies showed improved performance from this type of injection in the engine used, but other workers, using other engines and injectors, have had mixed results. Shakal has thus been developing a nonintrusive fiber optic viewing system which can image both the physical behavior of the spray and chemical species (OH, etc.). This research, which is still in progress, should help designers understand the reasons for pilot failures and successes and thus lead to improved designs.

Although the use of a real engine without significant modification is the best way to study sprays and combustion, the ability to do so is very limited by the engine geometry; thus the use of various rigs is also desirable.

Army Fellow Glenn Bower has thus used the engine-fed-bomb developed at the ERC to study spray behavior and combustion when using an advanced design prototype injector which allows pilot injection and modest changes in the shape of the main injection. Bower used a variety of techniques including high speed photography, exciplex mapping of vapor and liquid and two-color pyrometry to explore the effects of the pilot. The results are expected to be very helpful in validating models for the spray and for soot formation. These results should also be augmented by the work of Army Fellow Kevin Carabell who is using planar imaging by laser induced fluorescence to study the ignition of the spray in the engine-fed-bomb. This detailed understanding under engine conditions should greatly aid in validating recent work on ignition models for the CFD code KIVA being conducted at the ERC under a DOE contract. Carabell's work is still in progress.

Although spray breakup and vaporization are a major portion of the diesel fuel preparation process, modern high pressure sprays invariably impinge on the piston bowl, particularly during starting. A model for such impingement, co-authored by Army Fellow Jeffrey Naber, won the Horning Award in 1989. Naber then continued his work by an experimental study of droplet impingement. The extensive results of this study should have a significant impact on the ability to improve the impingement model in KIVA. This is of special interest to the Army, because it is a vital part of modeling the cold start problem.

Heat transfer and fluid motion both influence the behavior of in-cylinder events in the engine. The application of particle image velocimetry (PIV) allows study of the large scale motions important to the flow effects on spray and combustion behavior and also allows observation of near wall flows important for heat transfer. Army Fellow Jamshed (Jim) Ghandhi studied both of these phenomena in a motored two-stroke engine, showing the effects of geometry on flow and turbulence for the bulk flows and that three regimes of near wall flows exist. Some of the near wall flows showed that conventional boundary layer assumptions are not always applicable.

A similar attempt to measure near wall effects using laser Doppler velocimetry (LDV) was carried out by Army Fellow Philip Pierce. Although it was shown that LDV could not track to closer than 0.5 mm of the surface, much of the data gathered was used to help formulate new heat transfer models developed by other ERC students. Again, some of the data indicated that large velocities could persist to the wall.

Much of the behavior observed in the fluid flow studies was apparent in the heat flux measurements of Army Fellow David Boggs who developed a new multisensor heat flux instrument which allowed spatial resolution of flux to the head surface of a fired, homogeneous charge engine. Boggs showed that fluctuations in the flux could be used to define a heat flux length scale which seems to be similar in length to the bulk flow integral scale of turbulence. This new measurement technique gives further evidence that the conventional boundary layer concepts may not apply well to engines.

Extending the spray and fluid observations to combustion and emissions in real engines still requires much work. Thus direct study of the effects of fuels and combustion emissions is required as a separate topic. Fuel effects on emissions were thus studied by both Army Fellows Bob Bair and Dale Tree. Bair's study showed insensitivity of the emissions and combustion to the correlation between volatility and chemical species in the fuel. Tree showed that aromatics in the fuel and aromatic ring structure had little effect in a turbocharged diesel. Tree then went on to make in-cylinder measurements of soot particle size and number density. These results and the earlier work of Army Fellow Joe Hodges using a well-stirred reactor are being used to develop soot models for use in KIVA.

Although the ERC has concentrated on in-cylinder research as illustrated by the previously discussed research, a number of other projects were also carried out dealing with design aspects.

The work of Army Fellows Gerald Green and David Ruch at first appear quite different, however both are motivated by the interaction between the piston and liner. Green used finite element analysis to investigate the effects of design parameters on liner vibration which can cause water-side cavitation. Using the conventional slider-crank mechanism, Green has shown that both the liner design and the water side passage design influence potential cavitation. On the other hand, Ruch is working on an alternative drive mechanism which offers the potential reduction of liner vibration. In this new design, the hypocycloidal mechanism avoids side thrust on the piston. The mechanism should reduce noise as well as piston slap and upper reversal wear. The research included an evaluation of a prototype design.

Included in the topic of engine design is lubrication of the engine, especially the piston-liner which causes over one-half of the engine friction. Two of the Army Fellows, John Myers and Dana Richardson, studied lubrication by measurement of the oil film thickness on the liner of a TACOM/LABECO engine. Myers used a capacitance probe to measure upper ring reversal while Richardson used a new fiber optic method of laser induced fluorescence to measure at various locations on the engine and in a wear rig. Both sets of engine data suffered from poor oil control due to the piston design in this engine. The research has led however to a combination of these techniques on a modern engine at the ERC.

Although materials research was and is not a focus of the ERC, some fundamental work on ceramics was carried out by Army Fellow Dallas Meyer. The research concentrated on high-temperature response of ceramic composites.

A listing of the Fellows is given on the following page, followed by a summary of research for each Fellow.

SUMMARY OF ARMY FELLOWS

Ph.D. Fellow	Graduation Date	Current Employer	Thesis Title
Bair, Robert	Aug. 1989	John Deere	*Ignition Quality and Composition of Fuel Volatile Fraction: Effects on Diesel Combustion*
Boggs, David	Aug. 1990	Ford Motor Co.	*Spatially-Resolved Measurements of Instantaneous Engine Heat Flux*
Bower, Glenn	Aug. 1992	Post-Doctoral	*The Effect of a Split Injection on Early Combustion in an Engine-Fed Combustion Chamber*
Carabell, Kevin	Dec. 1992	Unknown	*A/F Ratio Measurements in a Diesel Spray*
Ghandhi, Jamshed	May 1991	Becton Dickinson	*Velocity Field Characteristics of Motored Two-Stroke Ported Engines*
Green, Gerald	Jan. 1992	John Deere	*Vibration Analysis of Cylinder Liners in the Consideration of Cavitation*
Hodges, Joseph	Jan. 1989	NIST	*Soot Formation in a Jet Stirred Combustor*
Knox-Kelecy, Andrea	Aug. 1992	Post-Doctoral	*Turbulent Flow in a Scale Model of a Diesel Fuel Injector Nozzle Hole*
Meyer, Dallas	Dec. 1990	IBM	*An Analytic and Experimental Investigation of the Rheology and Interfacial Mechanical Behavior of Ceramic Composites*
Myers, John	May 1989	Amoco Oil Company	*Factors Affecting the Top Ring Oil Film Thickness at Top Center*
Naber, Jeffrey	June 1992	Sandia Combust. Fac.	*Droplet Impingement on a Heated Surface*
Pierce, Philip	May 1991	Fiat	*Near Wall Velocity Measurements in a Motored Four-Stroke Engine*
Richardson, Dana	Aug. 1990	Cummins Engine Co.	*The Development and Implementation of Theoretical and Experimental Methods for Studying Oil Films in Engine Cylinders*
Ruch, David	Dec. 1992	Cummins Engine Co.	*An Experimental and Analytical Evaluation of a Single-Cylinder Modified Hypocyloid Engine Design*
Shakal, Joseph	Dec. 1992	MITI	*Effects of Auxiliary Injection on Diesel Engine Combustion*
Tree, Dale	June 1992	Cummins Engine Co.	*Soot Particle Size and Number Density Measurements in a Direct Injection Diesel Engine Using Light Scattering, Radiation, and Extinction*

SUMMARY OF RESEARCH FOR EACH FELLOW

In this section each of the fellows is highlighted and a brief abstract of the fellows' thesis research is given. This summary is followed by a listing of theses and publications of the fellows.

Robert Bair

Born: January 26, 1961 in Marshall, Minnesota

Prior Degrees: 1983 B.S., Mechanical Engineering, Kansas State University
1985 M.S., Mechanical Engineering, University of Wisconsin-Madison

Prior Employment: None

Present Employment: John Deere, Waterloo, Iowa

Major Professor: Gary Borman

Papers:

1986 "Diesel Combustion and Ignition Properties of Fuels with Different Volatile Fraction Constituents," with D. Boggs, G. Borman, and D. Foster, SAE paper no. 861539.

Doctoral Thesis Abstract (1989):

Ignition Quality and Composition of Fuel Volatile Fraction: Effects on Diesel Combustion

An experimental study was conducted to discern the nature of the mixture formation process in high and low swirl direct injection diesel engines. The study focused on the order of fuel component vaporization and burning. These tests were motivated by reports of distillation-like droplet vaporization in out-of-engine experiments. The principal parameters varied were ignition quality and aromatics content of the fuel volatile fraction, and swirl ratio. The effect of fuel sulfur-bearing component volatility on exhaust smoke was investigated.

Two sets of fuels were used to test fuel physical and chemical property effects. One fuel set was blended to have smooth boiling curves and bulk properties like typical D-2 fuels, but with modification of volatile fraction ignition quality and aromatics content. The second set had a radically changed volatile faction ignition quality. This set consisted of D-2 fuels blended with n-octane, a volatile, high ignition quality hydrocarbon. These fuels did not have smooth boiling curves. The sulfur study used a D-2 fuel doped with two sulfur-bearing hydrocarbons of different volatilities.

The experimental data included cylinder pressure, gaseous emissions, and smoke; it showed that ignition delay and emissions were insensitive to the fuel volatile fraction changes of the smooth boiling fuels in both engines. The low swirl engine was relatively insensitive to the changes of the n-octane blends. The ignition delays of the smooth boiling fuels correlated well with cetane number. This was not always true for the n-octane blends. Comparisons of smoke for the sulfur-doped fuels in the low swirl engine showed that fuel sulfur does change smoke. The more volatile dopant changed smoke more.

The bulk fuel cetane number is a valid indicator of ignition quality for the smooth boiling fuels set. The volatile fraction ignition quality is not disproportionately significant. Mixture formation was found not to be governed by fuel volatility. The order of fuel component vaporization was not rigorously determined, and will likely not be determined with this methodology.

Conclusions:

The ignition delay data show that the volatile fraction ignition quality does not disproportionately affect the ignition delay in the DI engine at medium-heavy-duty turbocharged conditions, for either low or high-swirl conditions. This extends the conclusions of Wong and Steere, who found similar results in a light duty DI engine. The emissions data, including Bosch smoke, nitrogen oxides, total hydrocarbons, and carbon monoxide, also showed no effect of the volatile fraction modifications, including the varied aromatics volatility of the fuels.

The changes in the volatile fraction properties of the fuels set were finessed, in that the smooth boiling curve constraint which was imposed at the time of blending seriously hampered the ability to effect large changes in the volatile fraction properties. That no effect of volatile fraction property modifications was seen for these fuels is perhaps not entirely surprising. However, the n-octane fuel blends did not have this constraint. The volatile fraction property differences produced with these fuels are much larger than could be reasonably expected in any foreseeable future D-2 diesel fuel. That no effect of these changes was observed is strong evidence that the fuel volatile fraction does not disproportionately affect the composition of the first fuel to burn. In fact, the influence of the volatile fraction for some of these fuels was less than would have been expected based on overall fuel property changes. The reasons for this lack of change are not clear. The data also show that the aromatics volatility does not influence the engine smoke emissions; this too is evidence that volatility is not the dominating factor in the mixture formation process.

Since volatility does not seem to be controlling the mixture formation process, some other mechanism(s) must be in control. One possible explanation of the ignition delay data obtained in this work is that the ignition delay is always controlled by the chemistry of the ignition process, rendering volatility changes to the high cetane components of a fuel inconsequential[1]. Another plausible mechanism is that small fuel droplets are swept out of the fuel sprays and are completely vaporized before combustion begins. This would cause the first fuel to burn to be compositionally similar to the liquid fuel. For the high swirl case, the droplets could be swept out of the spray by the swirl crosswind. For the low swirl case, the high injection pressures could produce droplets with significantly smaller diameters; these droplets could be swept out of the spray, perhaps by turbulence induced by the spray itself.

[1]This conclusion is supported by the work of Boggs and Van Gerpen.

David Boggs

Born: May 15, 1961 in Milwaukee, Wisconsin

Prior Degrees: 1983 B.S., Mechanical Engineering, University of Wisconsin-Madison
1985 M.S., Mechanical Engineering, University of Illinois

Prior Employment: None

Present Employment: Ford Motor Company, Dearborn, Michigan

Major Professor: Gary Borman

Papers:

1986 "Diesel Combustion and Ignition Properties of Fuels with Different Volatile Fraction Constituents," with R. Bair, G. Borman, and D. Foster, SAE paper no. 861539.

1991 "Calculation of Heat Flux Integral Length Scales from Spatially-Resolved Surface Temperature Measurements in an Engine," with G. Borman, SAE paper no. 910721.

Doctoral Thesis Abstract (1990):

Spatially-Resolved Measurements of Instantaneous Engine Heat Flux

Instantaneous heat flux rates were measured in a CFR engine. Two heat flux probes were used in the investigation. The first probe had five surface thermocouples in an iron body and was designed to measure the three-dimensional time-average heat flow at the surface in addition to the one-dimensional transient heat flux. The second probe had seven thin film platinum resistance thermometers on a Macor body and was designed to measure the spatial variations of the instantaneous heat flux. The integral length scale of heat flux was calculated from the heat flux data at each of the seven sensor locations of the Macor probe. A two-dimensional analysis of the transient heat conduction in the iron wall showed that the transient heat flows could be accurately approximated as one-dimensional.

Heat flux data taken with the thermocouple probe did not show significant differences with the shrouded intake valve producing swirl or tumble or with the unshrouded valve giving a relatively quiescent flow. However, the total heat transfer over all combustion chamber surfaces during the closed portion of the cycle (obtained from an energy balance) was higher for the cases where swirl was induced with the shrouded intake valve than for the cases where the shrouded valve promoted tumbling or an unshrouded valve was used. The effect of the pressure derivative on heat flux could not be assessed because temperature profiles and combustion-induced velocities also changed. The instantaneous heat flux varied substantially at the thermocouple locations which were just 2.4 mm apart, although the ensemble average heat fluxes were quite similar.

Integral length scales of the heat flux were typically 1 - 3 mm at TDC for motoring conditions, and were quite similar to the velocity length scales measured by others. The length scales did not scale with TDC clearance height, but were generally greater for swirl flow conditions than for tumble flow conditions. A comparison of motored cycles and fired cycles showed that the length scale increased more rapidly in the burned gases relative to the unburned gases.

Conclusions:

The first five conclusions concern the measurement of heat flux in the engine. 1) The thermocouple probe was not able to accurately measure three-dimensional time-average heat flows. This was because the probe was designed with an aspect ratio of the control volume that was too large ($\Delta z/\Delta x=4$). The probe should have had a subsurface thermocouple which was closer to the surface so that Δz was nearly equal to Δx. 2) The thermocouple probe was able to measure spatial variations of the instantaneous surface heat flux. The variations were caused by local fluctuations in the gas flow of both temperature and velocity. 3) Thin-film platinum resistance thermometers on a ceramic substrate had much better S/N than thermocouples and were able to accurately measure instantaneous surface temperature and heat flux in an engine. Time-averaged values for heat flux were not obtained with the ceramic probe. 4) It was possible to measure integral length scales at the wall for both motoring and firing cases using the Macor probe with the seven thin-film resistance thermometers. Heat flux intensities were also measured in order to quantify the temporal variability of heat flux. 5) The one-dimensional Fourier analysis technique is valid for calculating instantaneous heat flux rates in an engine despite the spatial variations of heat flux.

The next three conclusions concern the effects of flow patterns and turbulence, pressure derivative, and combustion on engine heat flux. 6) The thermocouple probe data showed no significant difference for heat flux with swirl flow, tumble flow, or a quiescent flow. However, the RTD probe data and global heat balances both showed that the swirl flow had higher heat fluxes than for either the tumble or the quiescent flow. Therefore, it is concluded that a stable mean flow increases the heat transfer rate over low-mean-flow cases. 7) The high frequency intensities (above 300 Hz) were higher for the tumble flow than for the swirl flow but were the same for the quiescent and the swirl flows. Since the heat flux for the swirl flow was 30% higher than for the tumble flow, and the heat flux was 70% higher for the swirl flow than the quiescent flow, it is concluded that turbulence intensity is also effective in increasing the heat flux. 8) The effects of the pressure derivative and combustion could not be assessed because the pressure variations were also accompanied by temperature changes and velocities induced by spatially nonuniform combustion, confounding the analysis. However, data were obtained that should be useful for verifying models. With models that can accurately predict combustion and velocities, the effect of the pressure derivative can be sorted out.

The following conclusions concern the length scales measured in the engine. 9) The TDC clearance height has no effect on the lateral integral length scales. 10) Swirl flows have greater length scales than tumble and quiescent flows. 11) The length scale increases rapidly in the burned gases, presumably because the high viscosity of the gases causes a rapid decay of the small scale eddies.

The following statement concerns the instantaneous heat flux measured in the engine. 12) Judging from the spatial variations of the instantaneous heat flux, and from the ability to measure length scales at the wall, it appears that turbulent eddies interact with the wall. This statement may be qualified by saying that eddies come close enough to the wall that the boundary layer thickness and the heat transfer rates are strongly modified by their presence.

Glenn Bower

Born: May 11, 1965, Port Huron, Michigan

Prior Degrees: 1985 A.S., University of Wisconsin Center-Richland
1987 B.S., Mechanical Engineering, University of Wisconsin-Platteville
1989 M.S., Mechanical Engineering, University of Wisconsin-Madison

Prior Employment: Co-op Engineer, James River Corporation, Green Bay, Wisconsin

Present Employment: Post doctoral research at the University of Wisconsin-Madison

Major Professor: David Foster

Papers:

1988 "Physical Mechanisms for Atomization of a Jet Spray: A Comparison of Models and Experiments," with S. Chang, M. Corradini, M. El-Beshbeeshy, J. Martin, J. Krueger, SAE paper no. 881318.

1989 "Interrogation of a High Pressure Injector," with D. Foster, Proceedings from the Central States Section of the Combustion Institute.

1989 "Investigation of the Characteristics of a High Pressure Injector," with D. Foster, SAE paper no. 892101.

1990 "Characteristics of a Variable Rate Shape High Pressure Injection System," with D. Foster, Proceedings from the ILASS National Conference.

1990 "Data from a Variable Rate Shape High Pressure Injection System Operating in an Engine Fed Constant Volume Combustion Chamber," with D. Foster, SAE paper no. 902082.

1991 "A Comparison of the Bosch and Zuech Rate of Injection Meters," with D. Foster, SAE paper no. 910724.

Doctoral Thesis Abstract (1992):

The Effect of a Split Injection on Early Combustion in an Engine-Fed Combustion Chamber

The research was done in a special designed engine-fed combustion chamber (swirl ratio of 5) with full field optical access through a quartz window. The simulated engine combustion chamber used as special backwards spraying injector (105°).

The electronically controlled injector could control the pilot injection's size and position. Both injections were through the same nozzle and it produced very rapid short injections (1.5 ms) with a maximum injection pressure of 130 MPa.

Experimental data included: rate of injection, injector pressure, combustion chamber pressure, rate of pressure rise, flame temperature, KL factor, NO and NO_x concentrations, spray plume images, tip penetration, and liquid and vapor fuel distributions.

Similar combustion was produced when the injection timing was adjusted to match peak combustion pressure. Also, the pilot and main injection should be located very close together (0.1 ms) with at least 50% of the fuel in the pilot injection in order to reduce NO concentrations and initial soot production. Using a split injection, peak rate of pressure rise was reduced by 25% and NO and NO_x concentrations were reduced by a factor of 3 and 2.5 respectively. The NO and NO_x concentrations, flame temperatures and KL factors were almost independent of the pilot/main distribution. A single main injection produced slightly higher flame temperature (75 K) while initially soot production was significantly higher (500%) but oxidized more rapidly. Tip penetration is very rapid and that it reaches a plateau at 25 mm. Exciplex images indicate

that fuel vapor reaches the outer regions of the combustion chamber beyond the liquid limits and the liquid droplets vaporizes quickly and uniformly throughout the spray plume.

These experiments indicate that the addition of a properly sized and positioned pilot injection causes lower soot production, lower NO and NO_x concentrations, and lower peak rate of pressure rise than an equivalent (fuel quantity) singe main injection.

Conclusions:

Further experiments were conducted with the injection timing being adjusted until the peak chamber combustion pressure was matched for three different injection cases. The different injections included: A) a single main injection, B) 50% of the fuel in the pilot and main injections with 0.1 ms between injections, and C) 70% of the fuel in the pilot injection and 30% of the fuel in the main injection with the main injection starting immediately after the pilot injection stopped. Matching peak injection pressures, case B injection started 1 ms before case A and 0.25 ms before case C. The peak rate of pressure rise for the split injection (case B and C) was only 75% of a single main injection (case A) even though the fuel was injected earlier in the cycle. The flame temperature and KL factor traces for injection case B and C were almost identical while case A had a slightly higher flame temperature (75 K) while initially soot production was significantly higher (500%) but oxidized rapidly to case B and C concentrations. NO and NO_x concentrations appeared to be independent of the pilot/main distribution but the use of a pilot injection reduced NO concentrations by a factor of 3 and NO_x concentrations by a factor of 2.5 over a single main injection. Images from the 105° forward scatter movies indicate that the tip penetration is very rapid and that it reaches a plateau at 25 mm. This is also supported by the exciplex images. The exciplex images also indicate that fuel vapor reaches the outer areas of the combustion chamber beyond the liquid limits. As the injection progresses, vapor phase fluorescence surrounding the spray plume image becomes more intense and starts extending beyond the spray plume area. When an injection ends, the liquid phase fluorescence disappears rapidly (<0.15 ms) while the liquid and vapor phase image appears like a spray plume image; the liquid droplets vaporizes quickly and uniformly throughout the spray plume.

These experiments indicate that the addition of a properly sized and positioned pilot injection causes lower soot production, lower NO and NO_x concentrations, and lower peak rate of pressure rise than an equivalent (fuel quantity) single main injection. If these results are repeatable in an engine, it would be a solution to the NO/soot tradeoff that has been observed with the use of a single main injection.

Kevin Carabell
Born: September 10, 1962 in Arlington, Virginia
Prior Degrees: 1984 B.S., Mechanical Engineering, University of Wisconsin-Madison
1989 M.S., Mechanical Engineering, University of Wisconsin-Madison
Intended Graduation: May 1993
Prior Employment: Westinghouse Electric Corp., Idaho Falls, Idaho
Intended Employment: Unknown
Major Professor: Patrick Farrell
Papers:
1990 "Planar Raman Scattering in Fuel Sprays," with P. Farrell, submitted for presentation at the Central States Section of the Combustion Institute.

Abstract of Doctoral Work in Progress:
A/F Ratio Measurements in a Diesel Spray

Quantitative models for the coupled mixing, vaporization and combustion process are available but need experimental data to ensure that the model is providing sufficient accuracy for a specific engine. Spray vaporization, fuel vapor mixing with the air charge, and subsequent autoignition in real diesels are extremely complex processes. Little is known of the composition, or the thermodynamic state of the mixture at the point of autoignition. The lack of this kind of data for the ignition process is limiting the development of better predictive computer models.

The objective of this project is to measure the composition and temperature of the mixture in the fuel spray that first ignites and the gradients in these properties around the point of ignition. The measurements will be nearly instantaneous, non-perturbing and spatially resolved. These measurements are to be made in an engine fed bomb with nearly unlimited optical access and geometry very similar to a direct injection diesel engine combustion chamber at the start of injection. Composition measurements will be made using iodine laser induced fluorescence (LIF). A Nd:YAG laser will provide the excitation and an intensified CID camera will be used to image the fluorescence. An infrared imaging camera will be used for temperature measurements. It is hoped that the data obtained can be used to further the understanding and modeling of the ignition of fuel sprays.

Jamshed Ghandhi
Born: April 5, 1961 in Whitefish Bay, Wisconsin
Prior Degrees: 1981 B.S., Mechanical Engineering, University of Wisconsin-Madison
1983 M.S., Mechanical Engineering, Massachusetts Institute of Technology
Prior Employment: None
Present Employment: Becton Dickinson, Research Triangle Park, North Carolina
Major Professor: Jay Martin
Papers:
1989 "Errors Associated with Laser Doppler Velocimeter and Phase/Doppler Diameter Measurements in Combusting Flows," with J. Martin, presented at the Central States Section of the Combustion Institute.
1992 "Near-Wall Velocity Characteristics in Valved and Ported Motored Engines," with P. Pierce and J. Martin, SAE paper no. 920152.

Doctoral Thesis Abstract (1991):

Velocity Field Characteristics of Motored Two-Stroke Ported Engines

The purpose of this study was to further understand the structure of fluid flow in the combustion chamber of an engine. Two combustion chamber geometries were studied, the pancake geometry and the bowl-in-head squish geometry. Two scavenging port geometries were also compared, a loop-scavenged Kohler engine and a loop-scavenged Mercury crankcase with a boost port.

Instantaneous planar velocity field measurements were made using particle image velocimetry. Data were taken at the mid-plane of the clearance gap of the motored engine. From these measurements, the velocity field and the vorticity field were computed.

Results from this study confirm that flow velocities scale with engine speed as does the vorticity. They also show that the boost port design effectively suppresses swirl at TDC. The Mercury pancake geometry showed a homogeneous flow field at TDC with no large scale motion. In contrast, the Mercury squish showed an organization cross-chamber flow which exhibited cycle-by-cycle variations in location.

Flow close to the wall was also studied. These results showed, due to the confined nature of the flow, boundary layer assumptions are often not applicable. Three regimes of near-wall flow were identified dependant upon the relative magnitude of the mean and fluctuating component of velocity.

Conclusions:

From these measurements, several observations were made:

1) The results were compared to previous work of Reuss et al. in motored and fired engines. While the magnitude of the velocities and vorticity were comparable, the structure of the flows were considerably different. The flows of Reuss were swirl dominated with a low relative level of turbulence. The flow field for these studies were scavenging flow of very fine texture with limited organized motion except for the case of the Kohler pancake geometry.

2) Two distinct porting systems were examined, a conventional loop scavenging engine, the Kohler, and a loop scavenged design with a boost port, the Mercury pancake. The Kohler

exhibited significant swirl component of velocity at TDC. The Mercury pancake showed little organized motion and appeared to be representative of homogeneous decaying turbulence.

3) Two distinct combustion chamber geometries were studied on the Mercury crankcase. The results of the test showed that, while the pancake geometry exhibited little organized motion at TDC, the squish geometry had areas of organized flow. This is evident in both the velocity and vorticity field presentations. Such a coherent structure could be the result of intake generated tumble or as the result of squish flow jet. In either case, the squish geometry exhibits a significantly different TDC flow field from either the Kohler pancake or the Mercury pancake.

4) Both the mean velocity and the mean vorticity were found to scale with engine speed. Likewise, the standard deviation of the velocity and vorticity also scale linearly with engine speed. The increase of vorticity indicates the level of turbulence scales with engine speed too.

5) Examining the flow field at the solid boundaries from both the quantitative data and qualitatively from streamline sketches, the flow-boundary interactions were classified into three regimes. The first are those flows with momentum deficit at the wall. This is typified by high mean velocity flows parallel to the wall and low relative turbulence intensity. In these flows, a classical boundary layer heat transfer model based on mean flow and turbulent transport properties would be most applicable.

The second regime are turbulent dominated flows with little mean flow. In this case, the turbulent eddies interact directly with the wall in a random fashion. Here a statistical model based on the bulk turbulent transport properties would most probably be required.

And finally, there exist regions of which exhibit both qualities of a moderate bulk flow and moderate turbulent transport. In these cases, some combination of the two would be applicable.

6) Finally cycle-by-cycle variations in the flow field were shown to exist. These frames from the identical operating condition were compared. All three contained similar large coherent structures though the exact direction and extent of these structures were different for each frame. Each frame also contained regions of small scale turbulence but the position of these structures also varied between the frames.

Gerald Green

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Prior Degrees: 1984 B.S., Agricultural Engineering, University of Nebraska
1986 M.S., Mechanical Engineering, Iowa State University

Prior Employment: Engineer, John Deere Product Engineering Center

Present Employment: John Deere Product Engineering Center, Waterloo, Iowa

Major Professor: Roxann Engelstad

Papers:

1993 "A Technique for the Analysis of Cylinder Liner Vibrations and Cavitation," with R. Engelstad, submitted to the SAE International Congress and Exposition.

Doctoral Thesis Abstract (1992):

Vibration Analysis of Cylinder Liners in the Consideration of Cavitation

The development of a model for the study of diesel engine cylinder liner vibration is presented. The procedure developed provides an analysis tool for addressing the cavitation erosion problem that occurs on the outer surface of cylinder liners. The modeling approach is based on the finite element method and includes the cylinder liner and the surrounding coolant using a fluid-structure interface between the two. The coolant on the outside of the liner has a large effect on the motion of the liner, therefore the structural problem and fluid problem cannot be decoupled.

Experimental studies were carried out in conjunction with the finite element model development to verify the numerical procedure. A modal analysis provides understanding of cylinder liner vibrations and the effect of the o-ring seals and the surrounding coolant on the liner motion. Data obtained in the time domain were used to determine damping coefficients for the liner, o-rings and water as well as the stiffness coefficients for the o-rings.

Application of the model demonstrate how pressures are generated and propagate through the cooling medium. The studies provide a better understanding of how and where on the liner surface the pressure in the water jacket can drop below the vapor pressure and thus cause cavitation. Parametric studies demonstrate design alternatives for reducing the minimum pressures that cause cavitation.

Conclusions:

Natural frequencies and mode shapes of the cylinder liner were identified. Characterizing the vibration of the cylinder liner is the first step in understanding cavitation, since it is the liner motion that causes the bubble formation and collapse. The different mode shapes showed two categories identified by the number of nodal circles in the axial direction. Zero order axial modes have no nodal circle occurring in the mid-span of the liner. The modes exhibited maximum displacements at the bottom of the liner and steadily decreasing displacements toward the clamped end. It would be these modes that would create the largest liner movement at the bottom of the water jacket.

The developed finite element model showed excellent correlation with experimental results. Without the water jacket, the experimental and finite element results were virtually equivalent for the first 2.0 msec after impact. Adding water to the model added some variability to the results, however, a good match in displacements and pressures was achieved up to 1.0

msec. The highest oscillations, in both displacement and pressure, occurred in the first 1.0 msec. Consequently, the model would work very well for studying the cavitation problem.

The mechanism creating the pressure fluctuations in the coolant can be attributed to the generation and reflection of acoustic pressure waves. Previous researchers recognized that the velocity of the liner surface generates pressure according to $v\rho c$. These same researchers did not however, account for the acoustic energy already in the fluid. After an impulse load is applied to the inside of the liner, the water pressure at the liner surface is initially equal to $v\rho c$. Soon after the start of the impulse, however, pressure waves generated at other locations on the liner have propagated around the liner and the reflected waves off the block walls create pressures different than $v\rho c$.

Joseph Hodges

Born: November 30, 1959 in Trenton, New Jersey

Prior Degrees: 1981 B.S., Mechanical Engineering, Purdue University

Prior Employment: None

Present Employment: NIST, Gaithesberg, Maryland

Major Professor: David Foster

Papers:

1990 "A Study on the Effects of Temperature on Soot Formation in a Jet Stirred Combustor," with H. Sato, D. Tree, and D. Foster, *Twenty-third Symposium (International) on Combustion*, The Combustion Institute, pp. 1469-1475.

Doctoral Thesis Abstract (1989):

Soot Formation in a Jet Stirred Combustor

Soot mass concentration, average soot particle size, incipient soot limit (ISL) and gas temperature were measured in a premixed Jet Stirred Combustor (JSC) fueled by toluene and air. The purpose of the measurements was to quantify the kinetics of soot growth in a turbulent backmixed combustion environment. Reactant stoichiometry, total mass flowrate and preheat temperature were parametrically varied.

It was found that at a given stoichiometry, the maximum burned gas temperature increased by approximately 300°C as the mass flowrate was increased from 0.75 g/s to 3.0 g/s. The ISL increased with flowrate in the interval 0.75 g/s to 2.0 g/s. At a flowrate of 2.1 g/s, the ISL reached a maximum and decreased as the flowrate was increased up to 3.0 g/s. For stoichiometries richer that the ISL, soot mass concentration was measured via extinction of laser light. It was shown that net rates of soot production can be inferred from mass concentration data in the JSC. The net rate of soot production was found to be very flowrate dependent and was minimized at a flowrate of 2.1 g/s. Below 2.1 g/s the temperature dependence of the sooting tendency was in accord with trends observed in laminar premixed flames. Average particle size and number density were measured via laser scattering and extinction.

A kinetic model of soot nucleation, coagulation and surface growth (applicable to homogeneous steady flow systems) was developed. In conjunction with the size and concentration data it was inferred that the soot nucleation rate was on the order of 10^{13} particles/cm^{3}s. The specific rate of surface growth was estimated to be of the order 10^{-4} g/(cm^{2}s). In comparison with laminar flame data, the soot nucleation rate in the JSC was found to be nearly 2 orders of magnitude less, whereas the surface growth rate was of the same magnitude. Thus, the relatively low sooting tendency in the JSC was attributed to low rates of soot nucleation. It was postulated that soot nucleation was suppressed due to the presence of relatively high OH concentrations which exist in the JSC due to backmixing of the products of combustion with reactants.

Conclusions:

The dependence of soot yield on equivalence ratio and mass flowrate was investigated. Below a threshold equivalence ratio of approximately 1.50, no soot was detected. The soot threshold equivalence ratio was found to be slightly flowrate dependent. The soot production rate, S_c increased by nearly a factor of 10 as the equivalence ratio was varied from 1.70 to 1.80.

Thus, beyond the soot threshold, small increases in the equivalence ratio caused the rate of soot production to increase rapidly. Since the rich blowout limit (maximum equivalence ratio for which stable combustion could be maintained) of the JSC corresponded to an equivalence ratio of approximately 1.90, the dependence of S_c on stoichiometry was investigated only over a very limited range of stoichiometry. The net rate of soot production, S_c decreased by a factor of 5 as the flowrate was increased from 0.75 to 2.1 g/s. With an equivalence ratio of 1.80 and mass flowrate of 0.75 g/s, the maximum rate of soot production was approximately 0.2%/msec. These trends were observed in hemispherical and spherical versions of the JSC.

For flowrates in the range (0.75 to 2.0) g/s, the data showed a decrease in the rate of soot production rate with increasing flowrate. However, beyond a flowrate of 2.1 g/s, the transition to a very sooty state occurred. The sooty flowrate range was characterized by a relatively low soot threshold equivalence ratio and high rate of formation of soot for stoichiometrics richer than the soot threshold. It was suggested that this transition may have been an artifact of a change in combustion kinetics associated with the approach to blowout in the JSC. At a given stoichiometry, as the mass flowrate is increased, the rich blowout limit of the JSC will be approached. With the approach to blowout, the conversion of reactants to products in the stirred combustor degrades. Hence, near the blowout limit, an excess of oxygen will develop. Studies of hydrocarbon pyrolysis in shock tubes have shown that within certain temperature ranges pyrolytic growth of soot will be enhanced in the presence of small amounts of oxygen. Thus, the transition sooty state as the flowrate was increased could have been directly related to blowout in the JSC. If this was so, then a correct interpretation of soot kinetics in a JSC must acknowledge the role of blowout and its effects on the combustion environment. Indeed, the JSC soot data of Blazowski showed an increase in the sooting tendency as the flowrate was increased. These results were shown to be in contradiction to the data of this study. The blowout effect was offered as an explanation of the disparity in the data. Due to experimental difficulties encountered while operating the JSC system at high flowrates, i.e., greater than 2.0 g/s, the transition region was not studied in as much detail as the low flowrate range. However, the abrupt change in sooting tendency of the JSC at 2.1 g/s is a phenomenon worthy of more investigation.

Andrea Knox-Kelecy

Born: August 30, 1961 in New Albany, Indiana

Prior Degrees: 1983 B.S., Mechanical Engineering, Purdue University
1985 M.S., Mechanical Engineering, Purdue University

Prior Employment: Staff Engineer, Process & Material Development Division, The Proctor & Gamble Co.

Present Employment: Post doctoral research at the University of Wisconsin

Major Professor: Patrick Farrell

Papers:

1992 "Internal Flow in a Scale Model of a Diesel Fuel Injector Nozzle," with P. Farrell, submitted to SAE Fuels and Lubricants Meeting, October, 1992, SAE paper no. 922308.

Doctoral Thesis Abstract (1992):

Turbulent Flow in a Scale Model of a Diesel Fuel Injector Nozzle Hole

An experimental investigation of the turbulent flow in a scale model of a high pressure diesel fuel injector nozzle has been conducted. Instantaneous velocity measurements were made in a 50X transparent model of one hole of the injector nozzle using an Aerometrics Phase Doppler Particle Analyzer (PDPA) in the velocity mode. The velocity data were analyzed for both average and spectral characteristics.

Length to diameter ratio (L/D) values of 1.3, 2.4, 4.9, and 7.7 and inlet radius to diameter ratio (R/D) values of approximately 0 and 0.3 were investigated. Two steady flow average Reynolds numbers (10,500 and 13,300), analogous to fuel injection velocities of 320 and 405 m/s and sac pressures of approximately 67 and 107 MPa (10,000 and 16,000 psi), were investigated. Spatially resolved mean and rms axial velocities, as well as the discharge coefficient, were obtained for both sharp and rounded inlet conditions and varying L/D. Also, the spatial variation of the turbulence spectra was obtained for each geometry.

The results showed significant differences between the sharp and rounded geometry rms velocity characteristics. Also, axial variations in the rms velocity characteristics were observed for the sharp inlet geometries. The spectral analysis results showed, similarly, significant differences between the turbulence spectra of the rounded and sharp inlets, revealing the axial progression of the spectra for each.

Conclusions:

Many of the findings of this study confirm what has been seen by previous investigators. For instance, the observed mean and rms velocity differences between sharp and rounded inlets were expected, and confirm previous results. The inflection point in rms wall velocity at the exit for L/D of approximately 4 was not expected, but does agree with behavior seen by previous researchers.

The L/D effects seem to be primarily limited to the sharp inlet holes. Therefore, controlling the hole L/D will be important if hole design and operation allow holes with sharp inlets. Exactly how the variations in near-wall rms values affect the spray breakup is still not ceratin and remains an area for further research. Perhaps the hole L/D could be used to produce the type of exit conditions desired, in sharp inlet holes, if the connection between the internal flow effects and the spray affects could be determined.

The spectral characteristics produced in the hole do not show concentrations of energy at specific frequencies but rather broadband turbulence, except for the low frequency pedestals seen for short sharp inlet holes. It is not clear how the turbulence power distribution affects the spray breakup for sharp holes. Perhaps for holes which show pedestals in the spectra, atomization is more likely to occur if dominant aerodynamic interaction frequencies fall within the range of the internal flow pedestal frequencies.

The spectral results did seem to show that for injectors with rounded-inlet holes (possibly rounded due to erosion as the injector "breaks in"), attention should be paid to the turbulence conditions upstream of the hole, since these seem to be passed on more readily by the holes with rounded inlets. This is a significant conclusion which should be considered by injector manufactures. This behavior could be used to an advantage. If the holes were made intentionally rounded, either by "breaking in" injectors or by machining and post-treating so that the inlets are rounded, desired frequencies which match dominant aerodynamic frequencies could be generated upstream of the hole and would still be present at the hole exit. Controlling the flow characteristics upstream while using a rounded hole could mean that L/D effects would no longer need to be a concern, and L/D values could be chosen based purely on desired hole diameters and material strength limitations.

Dallas Meyer

Born: September 8, 1962 :n Omaha, Nebraska

Prior Degrees: 1985 B.S., Civil Engineering, University of Nebraska-Omaha
1987 M.S., Civil Engineering, University of Nebraska-Lincoln

Prior Employment: Staff Engineer, Professional Service Industries, San Antonio, Texas

Present Employment: IBM Product Storage Division, Rochester, Minnesota

Major Professor: Reid Cooper

Papers:

1990 "Micromechanical Constitutive Modeling and Experimental Protocol for Ceramic Composites at Elevated Temperatures," with R. Cooper and M. Plesha, 14th Annual Conference on Composite and Advanced Ceramics, A.C.S.

Doctoral Thesis Abstract (1990):

An Analytic and Experimental Investigation of the Rheology and Interfacial Mechanical Behavior of Ceramic Composites

The purpose of this research is to evaluate the high-temperature mechanical response of the fiber-matrix interface in ceramic composites. This thesis introduces a new technique for evaluating and quantifying the mechanical response of these interfaces by comparing experiments to analytical simulations of bulk composite rheologic behavior. A decomposition of the displacement and stress fields of a composite specimen subjected to an "off-axis" compressional loading allows the simulation of creep and load relaxation by integrating a generalized two-dimensional boundary valve problem in time. The model incorporates nonlinear viscoelasticity in the matrix and a penalized incremental plasticity formulation for contract friction at the fiber-matrix interface. A Newton-Raphson solution scheme and a singular yield surface provision is developed for combining the effects of viscoelasticity and idealized Coulomb friction. The model solution predicts the existence of a steady-state stress field and strain rate for the composite, which is a function of the fiber orientation angle, the viscosity and the stress exponent of the matrix, and the friction coefficient of the fiber-matrix interface. To test the validity and usefulness of the model, an experimental protocol is developed to characterize the creep and load relaxation response of a calcium aluminosilicate (anorthite: $CaAl_2Si_2O_8$) glass-ceramic and the same material reinforced with *30 vol%* SiC fibers. Comparisons between the modeling and experimental results indicate that the interface is debonded with a substantial amount of cavitation. A friction coefficient of *0.4* to *0.7* is predicted for the interface response at *1310°C* and *1300°C*, respectively. An amorphous SiO_2 layer at the interface is observed to substantially affect the interface response. Comparisons between the model results and experiments are also used to quantify the matrix creep behavior in-situ within the composite: the conclusion is that the creep behavior is strongly influenced by stress with the stress exponent increasing from ~ *1* to ~ *3* as the compressive stresses increase from *7 MPa* to *~50 MPa*. This stress-deformation behavior of the matrix along with several other experimental observations indicate the primary deformation mechanisms of the matrix are diffusion at low stresses and mechanical twinning/dislocation glide at the higher stresses.

Conclusions:

A new approach has been introduced for evaluating and quantifying the high-temperature mechanical response of the fiber-matrix interface in brittle-matrix composites by comparing experiments and an analytical simulation of bulk composite behavior. The use of a generalized two-dimensional model incorporating an accurate numerical solution technique has been illustrated to be a very useful method for simulating the time-dependent response of a composite at elevated temperatures. A comparison of the model to the results obtained for a silicate-SiC reinforced composite system illustrates the ability of assessing the interfacial mechanical response based upon the steady-state creep rate of the composite.

There are a number of features that are in need of further examination, including improving the constitutive model to allow for the correct stress dependence of the matrix as well as to incorporate the ability to model the residual glass flow within the matrix. Relative to the latter part, the use of a continuum mixture theory formulation for two immiscible fluids for evaluating the rheology of ceramic partial melts and glass-ceramics is currently being pursued by the author. The use of load relaxation to aid in understanding the constitutive evaluation of the matrix behavior is also in further need of study. A more realistic constitutive model for the interface could also be developed, including features such as time-dependent deformations and tortuosity of the interface. As a final remark, the status of this project has arrived at a very natural break in the progression of the research as it relates to ceramic composites: the goal of developing a fundamentally based micromechanical model and experimental protocol for determining the usefulness of this methodology in evaluating the interface and rheological response has been achieved.

John Myers

Born: April 21, 1960 in Madison, Wisconsin

Prior Degrees: 1982 B.S., Mechanical Engineering, University of Wisconsin-Madison
1985 M.S., Mechanical Engineering, University of Wisconsin-Madison

Prior Employment: None

Present Employment: Amoco Oil Company, Naperville, Illinois

Major Professor: Gary Borman

Papers:

1988 "On the Computation of Emissions from Exhaust Gas Composition Measurements," with M. Myers and P. Myers, ASME ICE - Vol. 4, *Engine Emission Technology for the 1990's.*

1990 "Measurement of Oil Film Thickness and Liner Temperature at Top Ring Reversal in a Diesel Engine," with G. Borman and P. Myers, SAE paper no. 900606.

Doctoral Thesis Abstract (1989):

Factors Affecting the Top Ring Oil Film Thickness at Top Center

An investigation into factors influencing top-ring oil film thickness at TDC, in a diesel engine, was carried out using capacitance probes and surface thermocouples installed in the liner. Short term and long term trends in the data were observed, and many unexpected features were found.

The instrumentation proved both robust and sensitive. The capacitance gauges were capable of measuring the oil film thickness required, on the order of several μm, and also detected breakdown of the oil film and metal-to-metal contact. Significant, consistent differences in the film thickness around the cylinder were detected. The thermocouples showed that for this engine, the top ring unexpectedly cools the wall for a short time near TDC. Generally, the thermocouple data was more repeatable than the film thickness measurements, but did not seem to provide as much insight into the oil film phenomena.

One of the main characteristics of the data was found to be its lack of reproducibility. Consequently, two different data acquisition techniques were used. Acquiring consecutive cycles, for a short period of time, provided a "high resolution snapshot" of the process. Because of variability, however, this was not sufficient to characterize it. Taking non-consecutive cycles, over a longer period of time, provided much more knowledge about the long term trends in the data.

Despite the lack of reproducibility, changes in oil and operating parameters of large enough magnitude were detectable. For example, 1) the compression stroke always showed a thinner film than the exhaust stroke (70:1 pressure ratio), and 2) when the cylinder wall was wet by fuel, the film thickness dropped dramatically (20:1 viscosity ratio between fuel and oil).

The effect of the mechanical condition of the engine was found to be very significant; an under-sized piston was found to cause much metal-to-metal contact between the ring and liner, whereas a properly fitted piston showed practically none.

Variables that were not measured or controlled in this experiment but are thought to contribute directly to variability include ring motion, piston motion, cavitation, blowby, liner vibration, and particles in the oil.

Conclusions:

The following conclusions can be drawn from this study:

1) The factors affecting the top ring oil film thickness are more complicated than might first be thought. "Simple" hydrodynamic theory cannot predict the results, and there are indications that engine mechanical factors are as important, or more important, than oil factors. This is especially true given that the film thickness changes, even during steady state operation, with no known change in oil characteristics.

2) For the reasons given above, it seems unlikely that out-of-engine "rig tests" will accurately reflect results found in an actual engine.

3) Given the large amounts of variability, taking data for several hundred consecutive cycles is inadequate for complete characterization of the data. Long term "hopping" data should be used as the primary data acquisition method, and be supplemented by using the consecutive cycle technique.

4) If large enough changes are made in oil and operating parameters, differences can be seen. The compression stroke film thickness is always thinner than the exhaust stroke (70:1 pressure ratio), and when fuel wetted the walls, the viscosity effect was dramatic (20:1 viscosity ratio between fuel and oil).

5) The capacitance gauges work well and are very robust. (They survived the loose piston.) They are capable of measuring the required oil film thickness, and can also detect breakdown of the oil film and metal-to-metal contact. Their sensitivity is high enough to discern small differences between the three locations used for this study.

6) The thermocouples are durable, and are less variable than the capacitance gauges. On the other hand, they did not seem to provide as much information, and were not effective indicators of contact, as had originally been hoped. They did, however, show the reversal of the heat flux at TDC, which is significant.

7) Excess oil on the wall was shown not to have a large effect on the film thickness.

8) The variables that are actually controlling the film thickness are not known. Since oil flow to the cylinder wall did not seem to affect oil film thickness, it is thought that mechanical factors, as well as other factors not controlled in these tests, are the significant factors. Some of the possibilities include liner vibration, ring twist and lift, piston motion, cavitation, blowby, and particles in the oil.

Jeffrey Naber

Born: July 6, 1960 in Mukwonago, Wisconsin

Prior Degrees: 1986 B.S., Mechanical Engineering, University of Wisconsin-Madison
1987 M.S., Mechanical Engineering, University of Wisconsin-Madison

Prior Employment: U.S. Army

Present Employment: Sandia Combustion Research Facility, Livermore, California

Major Professor: Patrick Farrell

Papers:

1988 "Fuel Impingement in a Direct Injection Diesel Engine," with B. Enright and P. Farrell, SAE paper no. 881316.

1988 "Modeling Engine Spray/Wall Impingement," with R. Reitz, SAE paper no. 880107.

1992 "Drop Impingement on Heated Surfaces," with P. Farrell, to be submitted to SAE International Congress, February 1993.

Doctoral Thesis Abstract (1992):

Droplet Impingement on a Heated Surface

The heat transfer and hydrodynamics of a liquid droplet impinging on a heated surface were experimentally investigated. Also, an energy model for the spreading of a liquid film resulting from a droplet impingement was derived and validated.

Individual impinging droplet heat transfer measurements for liquid (water, acetone, and n-heptane) droplets (d = 100 - 300 μm, V = 2.4 - 7.1 m/s) were made for surface temperature from 56 - 400° C. The heat transfer decreased with increasing surface temperature as the heat regimes changed from evaporation-wetting, transition, to Leidenfrost.

High speed photography and image analysis were used to quantify the atomization resulting from the impingement of a droplet. Diameter and velocity distributions of the atomized droplets resulting from the impingement were determined. For the range of droplet sizes and velocities examined neither atomization nor splashing was observed in the evaporation-wetting regime. In the transition regime atomization was greatly influenced by surface temperature. The atomization of droplets impinging at surface temperatures above the Leidenfrost temperature increased with increasing impinging droplet Weber number.

A model based upon conservation of energy in the spreading film of an impinged droplet was derived. The model included the effects of surface tension, liquid viscosity, and contract angle in non-dimensional forms for the prediction of droplet impingement over a large range of conditions. Good agreement between experimental data and the model predictions were observed.

Conclusions:

The heat transfer per droplet that occurred during the impingement of the droplet on a heated surface was measured for 3 liquids, 2 diameters, and 3 velocities and reported in terms of the droplet effectiveness (η), a nondimensional quantity. Two principle conclusions were: 1) The effectiveness was found to decrease (from $\approx$ 1 to <0.2) as the surface superheat (T_s-T_{sat}) was increased from 0 to 300°C. 2) With comparisons to previously published data, an increase in effectiveness was observed for water as the We was increased at superheats ≥ 300°C (leidenfrost regime).

The impingement of droplets on a heated surface (at various conditions) were filmed with a high speed cine camera. For selected cases the results were quantified using image analysis. The principle conclusions reached were: 1) In the evaporation-wetting regime, for the droplet sizes and velocities examined, re-atomization as a result of impingement did not occur. 2) In the transition heat transfer regime, impingement atomization was observed to be affected by small changes in surface temperatures. 3) In the Leidenfrost regime, impingement atomization (increased number and reduced size) was observed to increase with increasing We. 4) At ambient pressures greater than the critical pressure of the liquid for impinging decane droplets, a Leidenfrost regime was observed at surface temperatures above the critical temperature of the liquid. At surface temperatures below the critical temperature with pressures above the critical pressure, the impingements were observed to be in the evaporation-wetting and transition heat transfer regimes.

An energy model that quantifies the various energy transfers occurring within a spreading liquid film (resulting from a droplet impingement) was derived. The energy model was used in the following ways: 1) Comparisons to available experimental data over a wide range of impingement conditions were made. The model results and experimental data were found to be in good agreement. 2) Predictions of the maximum film spreading resulting from a droplet impingement were made for impinging conditions typical of droplet impingements in a diesel spray.

Both the heat transfer and hydrodynamic results showed that droplet impingement was dependent upon the heat transfer regime. For the problem at hand, the heat transfer regime for the specific condition should be determined first, and appropriate models for that condition should be used. In a DI diesel engine, under normal operating conditions, the correct heat transfer regime appears to be in the evaporation-wetting regime. In port injected engines <u>all</u> heat transfer regimes are important.

The heat transfer results in this work not only give information on the heat transfer to the droplet, but could also be used as an estimation of the ratio of masses ejected from the surface to the impinging droplet mass, $\frac{m_{ejected}}{m_d} \approx (1-\eta)$.

The predictions from the energy model for the spreading of a droplet could be easily incorporated into submodels to predict film wetting.

Philip Pierce

Born: September 23, 1963 in Madison, Wisconsin

Prior Degrees: 1985 B.S., Applied Mathematics, University of Wisconsin-Madison

Prior Employment: None

Present Employment: Fiat, Toreno, Italy

Major Professor: Jay Martin

Paper

1988 "Heat Transfer Predictions and Experiments in a Motored Engine," with J. Yang, J. Martin, and D. Foster, SAE paper no. 881314.

1992 "Near-Wall Velocity Characteristics in Valved and Ported Motored Engines," with J. Ghandhi and J. Martin, SAE paper no. 920152.

Doctoral Thesis Abstract (1991):

Near Wall Velocity Measurements in a Motored Four-Stroke Engine

A laser Doppler velocimeter was used to measure gas velocity in the combustion chamber of a motored four stroke engine. The measurements were taken near two different surfaces at the same location on the cylinder head. One set of measurements were made with the optics in a forward scatter configuration near a protrusion from the cylinder head. The swirl component of velocity was measured at points ranging from the mid-plane of the clearance volume to within 50 μm of the protrusion. Some reduction in mean velocity was noted, but large velocities persisted to the wall. Turbulence intensities also maintained high levels from the mid-plane to the wall. A boundary layer was not resolved near the surface.

Measurements were also made near a flush mounted window in the cylinder head. The swirl component, radial component, and axial components of velocity were measured separately. Two speeds, 750 rpm and 1500 rpm, and two levels of swirl adjusted by the position of a shroud on the inlet valve were tested. The fluid motion in all cases was primarily in the swirl direction. Measurements were performed from the mid-plane to a point 400 μm from the surface. Index of refraction gradients prevented the measurements from being extended to the surface. Little effect of the wall on the flow was noted at this point. The turbulence in the engine was nonisotropic. The largest turbulent fluctuations were in the swirl component and radial component direction and were much larger than fluctuations in the axial direction.

A photographic test was performed to determine the range of distances over which refractive index gradients would shift the measurement, and it was found that measurements could be performed only to within 0.5 mm of the surface near TDC.

Conclusions:

A boundary layer was not resolved for either of the sets of measurements performed in the engine. Although the mean flow in the engine was largely parallel to the surface, little or no reduction in the mean flow was observed, and turbulence intensity levels showed little variation with distance from the surface at a range of crank angles for all the cases tested. For the measurements performed near the raised surface, it seems possible that turbulent fluctuations extend all the way to the surface as suggested by Boggs.

The turbulence in the engine flow is also very much a function of the mean flow. The turbulence intensity is largest in regions of large velocity, and is not isotropic, but demonstrated a much larger component in the direction of the primary mean flow, than in the axial direction normal to the cylinder head.

Another fact that became apparent in this measurement was that optical measurements can be strongly affected by the conditions in the flow field around the measurement. Beam steering prevented measurements of velocity closer than 400 μm from the surface by moving the image received by the detecting optics. Some method of determining the extent of the effect of refractive index gradients on the measurement must be employed, such as the photographic test employed here.

Dana Richardson

Born: April 29, 1962 in Salt Lake City, Utah

Prior Degrees: 1986 B.S., Mechanical Engineering, University of Arkansas
1987 M.S., Mechanical Engineering, University of Arkansas

Prior Employment: Engineer's Aide, Baldor Electric

Present Employment: Cummins Engine Company, Columbus, Ohio

Major Professor: Gary Borman

Papers:

1991 "Using Fiber Optics and Laser Fluorescence for Measuring Thin Oil Films with Application to Engines," with G. Borman, SAE paper no. 912388.

1992 "Theoretical and Experimental Investigations of Oil Films for Application to Piston Ring Lubrication," with G. Borman, to be presented at SAE Fuels and Lubricants Meeting, October 1992, SAE paper no. 922341.

1992 "Measurements and Modeling of Cylinder Liner Oil Film Thickness in a Motored Engine," with R. Phen and G. Borman, submitted for presentation at the 1993 SAE Congress, Detroit, Michigan.

Doctoral Thesis Abstract (1990):

The Development and Implementation of Theoretical and Experimental Methods for Studying Oil Films in Engine Cylinders

An investigation of the oil films in a diesel engine cylinder was carried out both theoretically and experimentally. A theoretical model was developed and used in designing the experiment on the engine. Theory was also used to show the effects of viscous heating and temperature gradients between the ring and liner.

A new laser induced fluorescent method using fiber optics for measuring oil films on the cylinder wall was presented. Initial tests of this system were performed on a static test rig. This provided information about the characteristics of the system. Sufficient signal can be obtained from the natural fluorescence of the oil, and it is very liner with film thickness. Results showed that the signal is affected by temperature and the additive packages in the oil. This indicates that a dynamic in-situ calibration is required when the fluorescent method is used in an engine.

Dynamic tests were performed on a Cameron Plint wear tester. These results showed that the fluorescent system is capable of measuring very thin film under dynamic conditions. The maximum and minimum film thickness and the trends observed correlated fairly well with the theory. Friction and contact resistance measurements were also taken.

The engine oil film data showed a high degree of variability, probably caused by reverse flow of oil through the drain holes behind the piston ring. To control oil consumption, this flow must be eliminated or decreased. Even those portions of the data that were repeatable do not show good correlation with theory. This might be due to the instabilities of the system or a lack of understanding of some theoretical aspect. However, data showed the passage of the ring pack, and that oil was being measured on the piston as well as on the liner.

Data from the engine and wear tester clearly showed oil starvation. The inclusion of this effect in the theory was necessary to obtain agreement.

Conclusions:

Theory was used as a tool to design and predict the behavior of the experimental studies that were to be done. The results from the theory can be divided into two areas, contributions to the theory and analysis using the theory. Only the main points of interest are brought out here.

Contributions to the Theory:

1) Temperature Effects--New equations were introduced that include the effects of temperature gradients in the calculations. With this theory, it was possible to show that viscous heating effects in the oil are negligible in a fired engine. It was also shown what effects temperature gradients between the ring and liner could have on the calculated results. The results show that it is a fairly good approximation to assume that the oil has the same constant temperature as the cylinder wall at any given point.

2) Vibration Effects--A simple vibration model suggests that the vibrations of the liner will not significantly affect the lubrication of the piston rings.

3) Rear Boundary Condition--Various results from the experiment were applied in attempting to verify the character of the rear boundary condition needed for the lubrication calculations. It was seen that the oil separates from the ring face rather than forming a bubble due to ventilation. Comparisons of calculations using different proposed boundary conditions to experimental results indicate that the Reynolds boundary condition fits the data best.

Analysis Using Theory:

1) Temperature--Theory dictated the need for accurate temperature measurements of the cylinder liner for the calculations to be reliable. It was specified that the temperatures need to be accurate to within about 5° C. Also viscosity correlations used should be within 10% accuracy.

2) Film Thickness Measurements--Theoretical results helped specify the ideal locations for film thickness measurements.

David Ruch

Born: November 1, 1960 in Vemillion, South Dakota

Prior Degrees: 1984 B.S., Mechanical Engineering, University of Cincinnati
1988 M.S., Mechanical Engineering, University of Wisconsin-Madison

Prior Employment: Test Engineer, Design Engineer, Reliability Engineer--Engineering Development Program, Aircraft Engine Business Group, General Electric Cincinnati, Ohio

Intended Employment: Cummins Engine Co., Columbus, Ohio

Major Professor: Frank Fronczak

Papers:

1988 "Experimental Determination of the Natural Frequencies of Hydraulic Systems under Flow and No-Flow Conditions," with F. Fronczak and T. Rida, *Proc. 43rd National Conference on Fluid Power.*

1991 "Design of a Modified Hypocycloid Engine," with F. Fronczak and N. Beachley, SAE paper no. 911810.

Abstract of Doctoral Work in Progress:

An Experimental and Analytical Evaluation of a Single-Cylinder Modified Hypocycloid Engine Design

The modified hypocycloid engine incorporates a unique geared drive that imparts straight-line, sinusoidal motion to the one-piece piston and rod assembly. These kinematic characteristics provide a variety of potential benefits not possible with traditional slider-crank kinematics. Perfect engine balance is achieved through the use of two sets of counterweights. The absence of piston side thrust promises reductions in piston assembly friction and piston slap, even with smaller piston skirts. Additional potential benefits include improved combustion characteristics and reduced piston manufacturing costs. Although simpler hypocycloid designs provide the same motion, the modified hypocycloid engine reduces gear and crankshaft loading.

A description and design details of a prototype single-cylinder engine are presented. Design improvements over previous hypocycloid designs are described. These improvements reduce crankshaft stresses, ensure a compact crankshaft with convenient assembly and disassembly, and control deviations form the ideal straight-line piston motion that are caused by gear tooth backlash.

A general evaluation is made of engine design features based on motoring and firing tests. This includes inspections of journal bearings, gear teeth, piston and cylinder, and other components. Recommendations for design modifications are made where appropriate.

Potential deviations from straight-line motion are analyzed and compared with static bending tests on the piston-rod. The significance of these deviations is discussed with respect to component loading and the practicality of a one-piece piston-rod. Measurements of system torsional natural frequencies are compared with predicted results and implications for engine operation are discussed.

Recommendations for future study are included in a general discussion of results.

Joseph Shakal

Born: September 22, 1964 in Bloomer, Wisconsin

Prior Degrees: 1986 B.S., Mechanical Engineering, University of Wisconsin-River Falls
1989 M.S., Mechanical Engineering, University of Wisconsin-Madison

Intended Graduation: December 1992

Prior Employment: None

Intended Employment: Japan's M.I.T.I.

Major Professor: Jay Martin

Papers:

1990 "Effects of Auxiliary Injection on Diesel Engine Combustion," with J. Martin, SAE paper no. 900398.

1992 "Inexpensive High-Speed Intensified CID Camera Controller," in publication of *A.I.P. Review of Scientific Instrumentation.*

Abstract of Doctoral Work in Progress:

Effects of Auxiliary Injection on Diesel Engine Combustion

It has been known that pilot injection and other forms of auxiliary injection can be used to improve power output, reduce particulate emissions and/or allow operation on substandard fuels in diesel engines for several decades. A significant amount of performance data have been published for specific engines, fuels, run conditions, and auxiliary injection techniques. In order to utilize auxiliary injection techniques, a predictive tool would allow engine designers to incorporate an auxiliary injection scheme without the need to gather engine data for an entire matrix of operating conditions. One of the first steps in forming such a tool is to understand the underlying reasons for the observed performance enhancements stated above.

It has been suggested that the auxiliary fuel can affect combustion of the main fuel in two ways: chemical and/or thermal. Knowing which of these pathways is predominant would provide a fundamental insight into the application of auxiliary injection techniques. For example, if the effect of a certain auxiliary fuel was determined to be primarily thermal, the auxiliary injection timing could be advanced to enhance this effect, but if the effect was primarily chemical, and reactive species were involved, retarding auxiliary injection timing would be beneficial.

The two-cycle test engine was prepared by installing a solenoid-controlled unit injector and two solenoid-activated air-assisted injectors. A personal computer was used to control these injectors by suitable hardware and software. The research effort began by obtaining performance and emission data for the test engine for three auxiliary injection techniques. Heat release calculations were included in the analysis of these data. Factorial analysis using four dependent variables was performed to determine what effect the fuel injection variables have on ignition delay, fuel consumption, heat release parameters, and each other. Optical access was obtained by modifying a pressure transducer port, thus resulting in minimal disturbance to the combustion system. An image guide along with both a film-type and a gateable intensified solid state CID camera were used to image the combustion chamber, near the injector nozzle. The ignition location was found by superimposing the combustion chamber and these images. A high-speed control circuit was built to interface the laser, intensifier, camera, frame grabber, and engine. An excimer laser excited the (A->X) O-O OH transition at 306 nm which allowed the spatial distribution of OH to be detected. Bandpass filters were used to detect spatial distributions of natural fluorescence from C_2, CH, HCO, CH_2HCO.

Dale Tree

Born: August 13, 1962 in Provo, Utah

Prior Degrees: 1986 B.S., Mechanical Engineering, Brigham Young University
1988 M.S., Mechanical Engineering, Purdue University

Prior Employment: None

Present Employment: Cummins Engine Company, Columbus, Indiana

Major Professor: David Foster

Papers:

1990 "A Study on the Effects of Temperature on Soot Formation in a Jet Stirred Combustor," with J. Hodges, H. Sato, and D. Foster, *Twenty-third Symposium (International) on Combustion*, The Combustion Institute, pp. 1469-1475.

1992 "Optical Measurements of Soot Particle Size and Number Density in a Direct Injection Diesel Engine," with D. Foster, to be submitted to SAE.

1992 "Soot Particle Size and Soot Volume Fraction Measurements in a Direct Injection Diesel Using Light Scattering and Extinction," with D. Foster, to be submitted to *Combustion and Science Techn-logy.*

1992 "The Effects of Fuel Aromatic Structure and Content on Direct Injection Diesel Engine Particulates," with M. Fukuda and D. Foster, SAE paper no. 920110.

Doctoral Thesis Abstract (1992):

Soot Particle Size and Number Density Measurements in a Direct Injection Diesel Engine Using Light Scattering, Radiation, and Extinction

In-cylinder soot particle size and number density have been measured in a single cylinder, direct injection diesel engine using principles of light scattering, extinction, and radiation. The measurements were made in a small volume approximately 1 mm in diameter and 4.2 mm long near the head over the bowl region. Two different measurement techniques were employed simultaneously and compared. The first method, radiation/scattering, involved measuring radiation from the soot along a line of sight and light scattering from a beam traversing the radiation volume. The second method used light scattering from the same measurement volume and extinction of the incident and returning light. Particulate and exhaust emission measurements were made to accomplish the in-cylinder results.

The results showed an assumed mono-disperse peak soot particle size in the range of 35 - 55 nm. Soot sizes were found to change rapidly in the measurement volume with particle sizes near 10 - 15 nm early in the cycle increasing to the peak and abruptly returning to sizes less than 25 nm near the end of combustion. Peak soot volume fraction and diameter were found to increase slightly with increased equivalence ratio. A combined change of decreased intake air pressure and retarded timing slightly decreased peak soot volume fraction and diameter in the in-cylinder measurements but decreased exhaust particulates by 2.5 times. The soot cloud was found to be dense and thick. Peak soot volume fraction varied from $3 - 7 \times 10^{-5}$ for the radiation/scattering method and from $4 - 11 \times 10^{-5}$ for the scattering extinction method. The soot was estimated to fill approximately half of the distance from the piston to the head or near 1 cm during the peak soot concentration portion of the cycle.

Conclusions:

The optical probe was successful at sealing combustion pressures and surviving engine temperatures. The windows remained clean at low loads for periods of 30-45 minutes which was long enough to take data. At higher loads the windows gradually experienced light soot deposition resulting in up to 40% attenuation after 1 hour of engine running. By calibrating before and after engine run, and limiting the data to one operating condition, the soot deposit errors could be reduced to less than 10%. A single fiber and spherical glass window were found to work well in introducing laser light into the combustion chamber. Heating from the laser light exciting the fiber and incident on the 3 mm spherical lens helped to keep the lens clean.

The results showed soot particle size and number density to be changing with time in the probe volume. Initially particles were seen around 15 nm in diameter. As time increased, larger particles were seen which reached a peak of 35-55 nm. The peak soot diameter was slightly dependent on equivalence ratio. Peak diameters from 45-50 nm were measured at φ=0.5 while diameters of 35-45 nm were measured at φ=0.2 and φ=0.3 for the radiation/scattering method. The scattering/extinction method gave slightly larger diameters with a maximum of 38-55 nm and showed more variability in the data. Soot particle size then decreased rapidly even though soot volume fraction or the soot mass was decreasing more slowly. Soot number density during the same time period increased. This decrease in diameter and increase in number density was attributed to one of two possibilities. The first was that the large soot oxidized rapidly in the combustion zone leaving smaller particles. The number density appeared to go up because of a shift in the shape of the size distribution from being weighted more heavily toward large particles to being centered around smaller particles. The later explanation is preferred because at some time the large soot particles disappear, no longer scatter, and are not seen by the probe. This means they must be oxidized and it would be difficult to imagine oxidation of so many particles without changing their size. Soot particle size decreased to about 15 nm where the signal from scattering became too small to measure and the soot concentration became too low for either measurement method to work. No conclusion could be made on exhaust diameter or number density because of the nature of the measurement methods.

Peak soot volume fraction and temperature were shown in both measurement methods to increase with equivalence ratio. The peak soot volume fraction was measured between 3 - 7 X 10^{-5} for the scattering/extinction measurement and 4 - 10 X 10^{-5} for the scattering/extinction measurement. These are similar values to soot volume fraction quantities measured in a diffusion flame. The soot cloud was found to be relatively thick, filling approximately 0.6 times the distance from the piston to the head. Peak temperature was found to increase from 2300K to 2500K as equivalence ratio was increased from 0.2 to 0.5.

PUBLICATIONS

Theses

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1992 An Experimental and Analytical Evaluation of a Single-Cylinder Modified Hypocycloid Engine Design, David Ruch.

1992 A/F Ratio Measurements in a Diesel Spray, Kevin Carabell.

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1992 Effects of Auxiliary Injection on Diesel Engine Combustion, Joseph Shakal.

1992 Soot Particle Size and Number Density Measurements in a Direct Injection Diesel Engine Using Light Scattering, Radiation, and Extinction, Dale Tree.

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Submitted for Publication

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1992 "Inexpensive High-Speed Intensified CID Camera Controller," J. Shakal in publication of *A.I.P. Review of Scientific Instrumentation.*

1992 "Measurements and Modeling of Cylinder Liner Oil Film Thickness in a Motored Engine," R. Phen, D. Richardson, and G. Borman, submitted for presentation at the 1993 SAE Congress, Detroit, Michigan.

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1992 "Soot Particle Size and Soot Volume Fraction Measurements in a Direct Injection Diesel Using Light Scattering and Extinction," D. Tree and D. Foster, to be submitted to *Combustion and Science Technology*.

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